

Can Light-nuclei Search Experiments Constrain the Spin-independent Dark Matter Phase Space?

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At present, restrictions on the spin-independent parameter space of WIMP dark matter searches have been limited to the results provided by relatively heavy nuclei experiments, based on the conventional wisdom that only such experiments can provide significant spin-independent limits. We examine this wisdom, showing that light nuclei experiments can in fact provide comparable limits given comparable exposures, and indicating the potential of light nuclei detectors to simultaneously and competitively contribute to the search for both spin-independent and -dependent WIMP dark matter.

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The direct search for evidence of weakly interacting massive particle (WIMP) dark matter continues among the forefront activities of experimental physics. Such searches are traditionally classified as to whether spin-independent (SI) or spin-dependent (SD), following the general decomposition of the WIMP-nucleus cross section into scalar and vector parts. Traditionally, the SI sector has been the most explored, with the current status of the search effort defined by a number of detectors which, because of their target nuclei spins, also provide the defining constraints on the SD phase space.

Generally, this dual impact is not considered a two-way street: the prevalent attitude is that exploring the SI sector of WIMP interactions requires nuclei with a high mass number because of the coherent enhancement of the scattering cross section, which scales with the squares of both the mass number and the WIMP-nucleus reduced mass. This is reflected in the thrust of new search activity based on detectors with germanium, xenon, cesium, tungsten, and iodine [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

We have examined this conventional wisdom in the case of several “light” nuclei experiments, which for discussion purposes are somewhat arbitrarily defined as $A < 25$. The main result of this Letter, which contradicts this “attitude”, is shown in Fig. 1. The reason lies in the loss of coherence in the scattering amplitudes as a result of the increasing nuclear recoil momentum. This is not to say that “heavy” nuclei devices do not provide more restrictive limits, all else being equal, but only that all is generally not equal and “light” nuclei devices cannot be *a priori* excluded from providing competitive restrictions on the SI parameter space given comparative exposures and sensitivity.

Fig. 1 is obtained from straightforward, standard projections of “light” nuclei results assuming isospin-independence [12], a 34 kgd exposure (active mass \times live time) equivalent to that of the current CDMS-II result, and an 8 keV recoil threshold (in order to focus on only the A -attributable differences). Since several of the “light” nuclei experiment techniques also possess back-

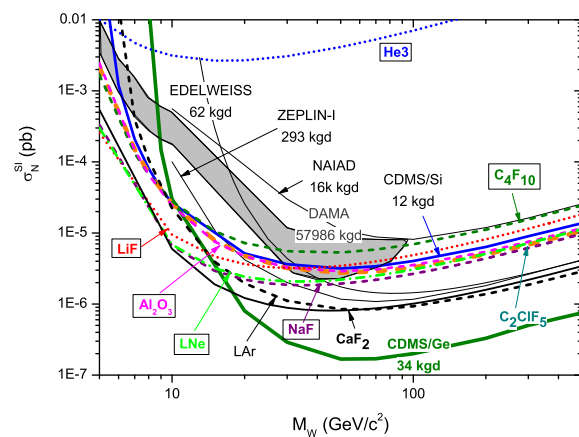


FIG. 1: projections of SI exclusion contours for various “light” nuclei experiments (broken), with a CDMS/Ge exposure, 8 keV recoil threshold and full background discrimination, in comparison with leading experiments (unbroken) in this sector.

ground discrimination capabilities, we further assume for the purposes of argument that the experiments are able to discriminate each of the observed events as background: with this assumption, it can be claimed that no WIMP has been observed, and the 90% C.L. upper limit on the WIMP rate is simply $\frac{\ln 10}{32} = 0.068$ evt/kgd.

These projections are shown in comparison with several leading SI experiments [13, 14, 15, 16, 17], which serve as benchmarks; the unexcluded region of the controversial positive DAMA/NaI result is shown as shaded. Although NaI contains sodium, we do not consider this as “light” since iodine is also present. This is similarly true for such other experiments using CaWO_4 [10], CaF_2 [18], ZnWO_4 [10] and CF_3I [11]. Similarly, C_2ClF_5 [19] is not considered “light” because of the chlorine presence, although the experiment is not generally considered “heavy”.

As seen in Fig. 1, several of the indicated “light” nuclei experiments would in fact provide restrictions on

the parameter space within an order of magnitude of some of the leading SI experiments which serve as reference. As also observed, the unexcluded spin-independent DAMA/NaI region is better probed by the “light” nuclei than CDMS/Ge.

Although at first sight the “light” nuclei impact in Fig. 1 may seem surprising, it can be understood from the spin-independent WIMP differential rate on which Fig. 1 is based [20, 21]:

$$\frac{dR}{dE} = \frac{\rho \epsilon(E)}{2M_W \mu^2} F^2(q) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv, \quad (1)$$

where E is the recoil energy of the target nucleus, ρ is the local WIMP halo mass density, M_W is the WIMP mass, σ is the zero-momentum transfer cross section, μ is the reduced mass, $F^2(q)$ is the nuclear form factor given by $\frac{\sigma(q)}{\sigma(0)}$ with q the momentum transfer, v_{min} is the minimum incident WIMP speed required to cause a recoil of energy E , v_{max} is the maximum incident WIMP speed, ϵ is the efficiency of the detector, and $f(v)$ is the WIMP velocity distribution function. The detector-dependent parameters are $\frac{\sigma}{\mu^2}$, F , ϵ and v_{min} ; v_{max} is simply the sum of the galactic escape velocity and the detector velocity with respect to the galaxy.

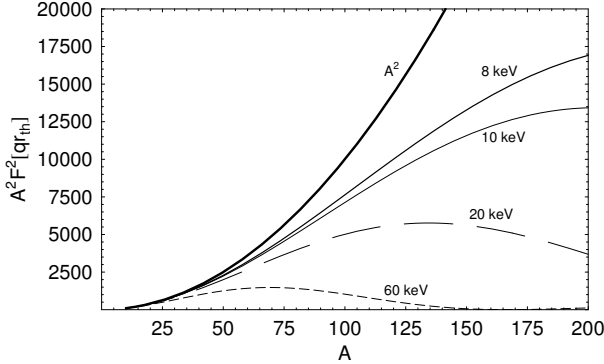


FIG. 2: Product of $A^2 F^2$ versus A , calculated for a Helm form factor and various E . The thick parabola shows the expectation of a simple A^2 scaling.

The projections of Fig. 1 employ the standard spherical isothermal halo, with a local density of $0.3 \text{ GeV}/c^2$, a halo velocity of 230 km/s , average Earth velocity of 244 km/s , a galactic escape velocity of 600 km/s , $\epsilon = 1$ (except in the case of the superheated liquids where $\epsilon = 1 - \frac{E_{thr}}{E}$, with E_{thr} the threshold recoil energy), and a Helm form factor [22] ($F(qr_n) = 3 \frac{j_1(qr_n)}{qr_n} e^{-(qr_n)^2/2}$) with nuclear radius $r_n = \sqrt{x^2 + \frac{7}{3}\pi^2 y^2 - 5z^2}$ ($x = 1 \text{ fm}$, $y = 0.52 \text{ fm}$, $z [\text{fm}] = 1.23A^{\frac{1}{3}} - 0.6$) [12].

As $\frac{\sigma}{\mu^2} \propto A^2$, the SI exclusion capability of a nucleus is significantly enhanced by its mass number, as per conventional wisdom. Moving from $A \sim 20$ (F) to $A \sim$

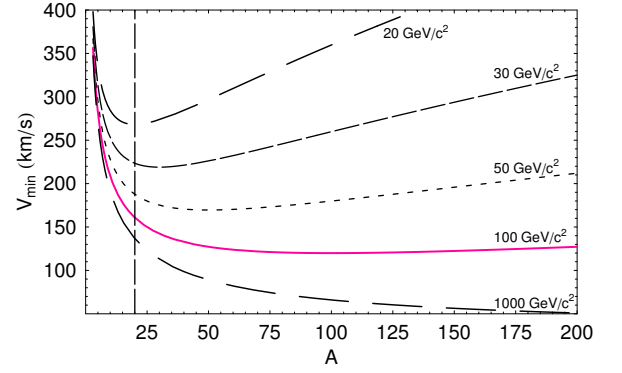


FIG. 3: Minimum WIMP speed for 8 keV recoil energy and various M_W .

200 (W) however only provides a 2 order of magnitude shift, which is reduced by the higher momentum transfer corresponding to the high recoil energy bins of large A experiments, unless the analysis is limited to the lowest energies. Fig. 2 shows the variation in the product $A^2 F^2(q)$ with A for various recoil energies. As evident, for low recoil energies $A^2 F^2(q)$ increases along the entire range of nuclei, although above $A \sim 40$ the growth is weaker than the simple A^2 scaling. At high recoil energies, the heavy nuclei lose some of their effectiveness as WIMP detectors. This is particularly evident in the 20 keV curve, where iodine has a maximum sensitivity. For iodine recoils in a NaI detector, this curve corresponds to 1.8 keVee , while the 60 keV curve, where iodine has lost most of its spin-independent sensitivity enhancement in favor of Ge, corresponds to 5.4 keVee .

The impact of the integral in Eq. (1) on experimental sensitivities can be discussed in terms of its lower limit:

$$v_{min} = \sqrt{\frac{E_{thr}}{2Am_p}} \left(1 + \frac{Am_p}{M_W}\right), \quad (2)$$

where m_p is the proton mass, and the small difference with the neutron mass is neglected. Clearly, the lower the v_{min} , the larger the inverse velocity integral in Eq. (1), and whenever $v_{min} \geq v_{max}$ the rate vanishes. Hence a WIMP sensitive experiment should have a low v_{min} , otherwise the detector misses a significant fraction of the recoils within its sensitive volume, which translates to a loss of constraint even with full particle discrimination. Low v_{min} can be pursued by lowering E_{thr} , but inspection of Eq. (2) shows that the detector composition has a nontrivial effect: v_{min} has an absolute minimum for $Am_p = M_W$, so that for $M_W \geq 200 \text{ GeV}/c^2$ a “heavy” isotope is an advantage, but for low M_W , as visualized in Fig. 3 for $E_{thr} = 8 \text{ keV}$, this is not the case.

The strong increase of v_{min} below $A \sim 10$, visible for all the displayed WIMP masses, reduces the fraction of the incident WIMP spectrum detectable by these experi-

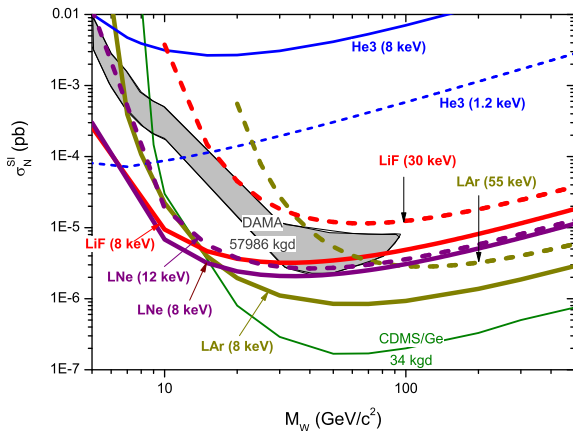


FIG. 4: comparison of the projected exclusion contours of several “light” nuclei experiments (unbroken) in Fig. 1 with identical projections assuming more realistic recoil threshold energies (dashed).

ments, unless a strong effort to lower the recoil threshold below ≈ 8 keV (hence to reduce/discriminate the low energy background) is successfully made. The question if at low M_W a lower inverse velocity integral due to the choice of “heavy” nuclei overcomes the benefit from the $A^2 F^2(q)$ scaling does not have a straightforward, $f(v)$ -independent answer, because this integral depends on the actual $f(v)$ and v_{max} . Assuming the same isothermal halo of Fig. 1, Fig. 4 shows the effect of threshold reduction for the LNe, LAr, LiF and He3 experiments: clearly, the most stringent contours for each result from the lowest threshold operation, all else being equal.

Also observed in Fig. 3 is that in a low WIMP mass scenario with $M_W \approx 23$ GeV/ c^2 , the DAMA annual modulation signal can be tested through isotopes in the range $A = 15$ -30. The NaF bolometers [23] are probably the most suitable existing detectors alternative to NaI for this purpose since both nuclei are Na-similar (the low M_W limit of DAMA is dominated by Na).

Whether or not “light” nuclei experiments can actually achieve the larger exposures required to be competitive with the heavier nuclei devices remains in question, since most have reported only low active mass, low exposure prototype results, without background discrimination and with thresholds well above their theoretical capabilities, as indicated in Table I. The searches based on Al_2O_3 , LiF, NaF, and He3 are all cryogenic. The CRESST-I successor, CRESST-II, however pursues CaWO_4 [10]. Both the LiF and NaF results derived from several bolometers with thresholds ranging between 8 and 60 keV, the impact of which is shown in Fig. 4. Apparently, these resulted from excessive noise which could not be reduced, and the experiments have been superseded by a 310 g CaF_2 scintillator [18]. ROSEBUD, with plans for a mass increase to 200 g, would require only a 170 kgd

exposure to achieve the CDMS contour, which could be accomplished with a 5 kg active mass in 34 measurement days. Similarly, the LiF and NaF would require exposure increases to 680 and 450 kgd, respectively, which a few kg active mass could achieve in reasonable measurement times. The active mass is limited by the size and cooling power of the refrigeration unit to \sim factor 20 less than the noble gas experiments, and requires some financial consideration in view of the milliKelvin operating temperatures. All would profit from background discrimination, using either ionization or scintillation in addition to heat, with the disadvantage that the small scintillation signal of nuclear recoils is produced by only relatively high energy WIMP events.

The C_4F_{10} -based activity is a superheated liquid project, with a 330 kgd exposure of 4.5 kg active mass currently in progress which would improve the results to below 10^{-6} pb. Such devices offer an intrinsic insensitivity to the majority of common search backgrounds, equivalent to an intrinsic rejection factor several orders of magnitude larger than the bolometer experiments with particle discrimination; the result is a sensitivity to only high stopping power interactions, beyond that of nuclear recoils. They however do not so far offer a background discrimination beyond their intrinsic insensitivity.

To reach the CDMS contour above $M_W = 100$ GeV/ c^2 would require of a He3 experiment $> 3.4 \times 10^4$ kgd exposure, or $> 10^3$ d with the 10 kg device proposed [28]. This is reduced to ~ 1 year if only the $M_W < 20$ GeV/ c^2 region is in question. Neither of the existing efforts (Table I) has yet produced a result.

The LNe approach is similar to that of xenon (ZEPLIN-II [31], XMASS [9], XENON [8]) and argon (ArDM [32], DEAP [33], WARP [34]), with a capacity to identify nuclear recoils. A projected 10 fiducial ton device is expected to yield a minimum in the limit contour near 10^{-10} pb, but the activity has yet to provide a result. An advantage of this technique is however that once demonstrated, it can be rapidly scaled up to significantly larger mass.

In contrast, CDMS is about to start a 5 kg active mass experiment, which is expected to improve on its current result by an order of magnitude; this is to be followed by upgrades to 25 kg and eventually 1 ton [5]. ZEPLIN-II has just reported a 32 kg result, with a contour minimum of $\sim 7 \times 10^{-7}$ pb at $M_W = 70$ GeV/ c^2 ; XMASS is preparing a 100 kg active mass experiment, and XENON is operational with a 15 kg active mass. Of the LAr experiments, only WARP has produced a first 96 kgd result with a double phase, 1.83 kg active mass device operating with a 40-55 keV threshold, achieving a minimum of $\sim 10^{-6}$ pb at 90 GeV/ c^2 ; an upgrade to 186 kg active mass is already underway. DAMA/LIBRA [3], an upgrade of the DAMA/NaI experiment to 250 kg with improved radiopurity, is running since 2003; R&D is in progress for a mass upgrade to 1 ton. A second NaI ex-

TABLE I: survey of “light” nuclei experiments, including projections from new initiatives (*).

detector	mass (kg)	exposure (kgd)	E_{thr} (keV)	contour min. (pb @ GeV/c ²)	approach	experiment [Ref.]
Al ₂ O ₃	0.262	1.51	~ 1	10 ⁻³ @ 30	cryogenic	CRESST-I [24]
	0.050	0.11	~ 2	10 ¹ @ 50	cryogenic	ROSEBUD [25]
LiF	0.168	4.1	8 - 61	10 ² @ 30	cryogenic	Kamioka/LiF [26]
NaF	0.176	3.38	12 - 37	20 @ 20	cryogenic	Kamioka/NaF [23]
C ₄ F ₁₀	0.019	1.98	6	~ 1 @ 30	superheated liquid	PICASSO [27]
*He3	10	-	~ 1	-	superfluid	MIMAC [28], ULTIMA [29]
*LNe	5	-	~ 12	-	noble liquid	CLEAN [30]

periment, ANAIS, reports an exposure of 5.7 kgy with a 10.7 kg prototype [35], and will be eventually upgraded to 100 kg.

In short, whether or not “light” nuclei experiments will contribute to the direct search for SI WIMP dark matter depends on whether or not they are able to close the gap with their more developed, larger “heavier” colleagues. They however could contribute, given comparable development and support.

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